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THE PRINCETON PENNSYLVANIA ARMY AVIONICS RESEARCH PROGRAM

Final Report

SYSTEM STUDY OF LANDING

by

Dunstan Graham

March 1972

Contract DA28-043 AMC-02412 (E)
The Trustees of Princeton University
Princeton, New Jersey

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For

U. S. Army Electronics Command, Fort Monmouth, New Jersey

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Using the tools of feedback system analysis and simulation a study has been made of the limitations on helicopter approach and landing under conditions of low visibility. It is shown that relatively steep approaches to low decision heights can be made on instruments. Successful loop topologies were identified and considerable improvement over the standard GCA approaches was shown to be possible with a scanning beam system especially if beam rate signals were empolyed. Errors introduced by turbulence and wind shear were the dominant ones. An automatic approach system could be mechanized using the same signals as the manual approaches which were considered.

FOREWORD

The work reported here was performed at Princeton University under the Princeton Pennsylvania Army Avionics Research (PPAAR) Program. The work was supported under Contract DA 28-043 AMC-02412 (E), DA Project #1 H 1 62202 A 219, Avionics Technology: Task 07, Avionics Techniques Studies. Professor Dunstan Graham served as Task Investigator for the Contractor. Mr. Joseph T. Saganowich was the U. S. Army Electronics Command Technical Associate whose encouragement and constructive criticism helped to shape the program. The work was accomplished between 1 September 1966 and 30 June 1968.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

The objective of the research reported here has been to determine the limitations which are placed upon the operational capability of the helicopter in approach and landing by the guidance, display, pilot and machine itself - in combination. It has been specifically intended to examine guidance system parameters needed for low visibility approaches in helicopters. The effort has been in direct support of Avionics Laboratory's planned landing system program, the first goal of which is the development of a tactical, ground based, radio guidance system for helicopters. It is expected that theoretical analysis, will be a valuable adjunct to the planned flight research approach to the problem.

In the first ten months on this research we formulated an approach to the systems problem and gathered background material on the system elements, namely: guidance, vehicle characteristics, forcing functions, and pilot models. In addition some preliminary longitudinal closed-loop analyses of helicopter control in landing approach were accomplished and the means for defining the success of the approach were outline. All this was reported in the first year's annual report (Ref. 1).

During the subsequent period covered by this report (1 July 1967 to June 1968) the closed-loop analyses were carried forward so as to include both longitudinal and lateral control of both a typical single-rotor and a typical tandem-rotor helicopter (Ref. 2). With these results in hand, a simulation of pilot control of instrument low approach in helicopters was set up and was exercised so as to yield data on:

- the effect of the addition of beam rate to the control signals in both the vertical and lateral dimensions

- the improvement to be expected from the use of scanning beam guidance as opposed to the use of the conventional GCA

- the influence on approach success of the addition of a pitch damper to the control system

- the influence of scanning delay in a scanning beam approach guidance system

- the influence of the geometric glide path angle

- the effect of varying degrees of the severity of atmospheric turbulence

- the effect of varying vehicle characteristics and trimmed flight condition

- the effect of wind shears on the accuracy of following the beam

- the minimum glide path angle for a specified level of safety with respect to obstacle clearance

- the signals required to be displayed to the pilot or employed in an automatic approach control system

These results have been reported in Ref. 3 and 4 and are described below.

II. THE SYSTEM DESIGN PROCESS FOR AN APPROACH SYSTEM

The system design process for a pilot-vehicle system is similar to the one employed in the design of inanimate systems. It comprises at least four significant steps:

1. definition of the purpose of the system

2. definition of the environment in which it is to operate

3. evaluation of the capabilities of subsystems and components (including the human operator) and the synthesis of competing systems

4. application of criteria for system performance and the selection of the "best" system.

Figure 1 shows how we may begin to study the system design of an approach system comprising a helicopter or VTOL aircraft, a human pilot, and an approach guidance system. The purpose of the system is to make steep IFR approaches (considering first only longitudinal control). This is also the mission phase. Guidance possibilities include at least a scanning radar with voice communication (GCA) and a radio beam system or its equivalent. The aircraft operating point is steady descending flight. (It is considered premature to study decelerating flight paths for IFR approaches without first understanding steady flight.)

The vehicle characteristics which we shall be compelled to consider will be strongly dependent on the particular operating point which is selected. Figure 2 illustrates some of the factors which influence the

choice of an operating point. It shows the interplay of airspeed (no-wind groundspeed), rate of descent, and glide slope. Superposed on the graph are two "forbidden" regions, the region of roughness and the region below the autorotation boundary. In order to stay well away from these regions and in order to minimize the influence of longitudinal gusts on control of the rate of descent, it is desirable not to fly much slower or steeper than the recommended operating point shown as the cross-hatched square. Of course, it is easily possible to fly faster or at shallower glide path angles, but then much of the unique performance capability of the helicopter would be obviated.

The environment in which the vehicle operates is simply the atmosphere, and the forcing functions are gust velocity components of an assumed isotropic turbulence.

III. ELEMENTS OF THE SYSTEM

The elements of the system are the ground based guidance, airborne guidance receiver, other airborne instruments, the displays, the pilot, and the vehicle including its control subsystem.

We shall consider two basic types of ground based guidance equipment. The first is a scanning radar with voice transmission of the indicated path errors. This is the so-called "no gyro" GCA. It represents the standard method for providing approach guidance for helicopters in use in the U. S. Army today. Observation of practice hooded approaches at Ft. Rucker, Alabama, indicated that the mean rate of transmissions for the correction of errors in the vertical plane is one every 14 sec and the mean rate of transmissions for the correction of lateral errors is one every 10 sec. We take it that a suitable model of this system element is approximately the measurement of deviation from the glide path lagged by 14 sec and deviation from the "localizer" lagged by 10 sec.

The other guidance equipment is an idealized radio beam system in which the deviation from the glide path is measured practically instantaneously and in which the measurement of range to the aircraft is used to provide course softening. Later we shall wish to consider a further idealization in which height rate with respect to the glide path and lateral deviation rate with respect to the localizer are also available as outputs of the receiver. Lags and other imperfections in the receiver are for the moment, neglected.

Standard indications of pitch and roll attitudes, heading, airspeed, and barometric rate of climb/descent are assumed to be available. The first four of these are indicated with negligible lag while the lag in the indication of rate of descent is notorious. This lag is taken to be 0.4 sec.

A model for the human pilot is the simple describing function form,

$$Y_p(s) = K_p e^{-\tau_{eff} s} \tag{1}$$

where the gain, K_p, is adjusted for good system performance, and the effective time delay is taken to be 0.4 sec to account for scanning and sampling delays as well as for time delays and lags in the neuromuscular system (Ref. 5 - 7). Where it may be required for stability, the pilot can also introduce lead so that the describing function then becomes:

$$Y_p(s) = K_p e^{-\tau_{eff} s} (T_E s + 1) \tag{2}$$

T_E might be as large as 5 sec (Ref. 5 - 7).

The vehicle and its control system are represented by the liniarized equations of motion of a typical single-rotor helicopter. The controls of interest are the collective pitch control and the longitudinal cyclic pitch control. Lags in the control system are neglected as indeed are also any lags in engine speed governing. The operating point condition is taken to be 40 knots on a glide path of -14 deg. Lacking any better information, however, the stability derivatives were based on measurements and estimates of the derivatives in level flight. (Recent model measurements for the XC-142, made on the Princeton long track, showed little difference in the dynamic motions between level and descending flight, and a check of our simulation with substantial changes in the drivatives suspected of being most sensitive to rotor throughflow again showed that the results were very little, if any, different.) The dynamics of the vehicle under the action of multi-loop feedback control were studied by means of servoanalysis techniques (Ref. 2, 8, 9).

IV. SYNTHESIS OF THE LOOP CLOSURES

The multi-loop analysis showed the best fashion in which motion variables of the vehicle should be used to control the vehicle's dynamic motions (Ref. 2). Figure 3, for example, shows that pitch angle and pitch rate feedbacks to the longitudinal moment control (cyclic pitch) corrects the unstable phugoid of the vehicle and provides adequate pitch damping. The additional feedback of velocity error to cyclic pitch, Fig. 4, provides some additional stabilization of the low frequency mode (phugoid). The feedback of height to collective pitch, Fig. 5, is used in preference to the feedback of height to cyclic pitch because it provides by comparison, increased height control bandwidth (i.e. "tightness of control"). These feedbacks, taken together, are basically a representation of the manner in which the human pilot controls a helicopter in the longitudinal plane. Similar analyses were made for lateral control (Ref. 2).

V. SIMULATION

In the simulation study the pilot model was placed in the system so that the appropriate aircraft output motion variables would be used to move the controls (Fig. 6, 7).

The analog computer simulation started with the basic longitudinal and lateral equations of motion for the H-19 single rotor helicopter. The two sets of three-degree-of-freedom equations of motion were each solved simultaneously on the analog computer so as to yield the motion variables (Ref. 10, 11).

External disturbance inputs to the system come from atmospheric turbulence and the pilot remnant, both of which are noise with definable power spectral densities. The form of the gust model of Etkin (Ref. 10) was used for the spectrum of atmospheric turbulence. Values of the root mean square gust velocity, σ, and scale length, L, however, were determined from data given by Pritchard (Ref. 12). (The root mean square gust velocities were made approximately 10% larger than they might otherwise have been to approximately represent the effect of the pilot's remnant.)

A transient analog, an impulse input to a first order filter in which the impulse intensity was proportional to the zero frequency intensity of the gust spectrum and the time constant was numerically equal to the break frequency of the gust spectrum, was used as the actual disturbance input to the simulation (Ref. 13-15). The formula for the transient analog of the Etkin gust spectrum is simply

$$r(t) = \sqrt{300}\,\frac{\sigma}{2}\,e^{-\omega t} \tag{3}$$

where:

σ = rms gust velocity

$\omega = \frac{3}{2}\frac{U_o}{L}$ = spectral break frequency

L = scale length $\doteq$ 100 ft

U_o = flight velocity

The convenient use of the transient analog allowed a direct reading of the mean square height error output and overcame the messy problem of evaluating the statistics of time dependent functions which would be associated with using a random process as the input. The transient analog was easity varied so that the effect on the system of 12 different inputs, representing turbulence from rather severe conditions to very light conditions, could be quickly evaluated.

Ultimately no account was taken of inaccuracies in the received position data from the scanning beam guidance system. The performance

claimed for the equipment showed that indicated errors at ranges typical of the final stages of the approach would be measured in fractions of a foot. (At longer ranges the errors would be much less important.) Since the turbulence induced errors in tracking the approach path were shown to be of the order of magnitude of several feet and the total rms error would presumably be represented by the square root of the sum of the squares, the inaccuracies in the received radio signal should be truly negligible in determining the close-in system performance, provided the claimed performance for the radio guidance system is actually achieved.

System dynamics were checked using the response to initial errors with no disturbance (Figs. 8, 9 and 13). All reported rms errors (Figs. 10 and 14) were calculated from simulated approach runs which included various disturbances.

IV. DISCUSSION OF RESULTS

A. Longitudinal Case

In some cases, the insertion of the pilot time delay, τ, in the control loops necessitated large changes in the gains of the feedback loops with respect to those obtained in the no-lag multi-loop analyses of Ref. 2. The loop closure gains finally used were determined by considering, in order of importance, first the overall system stability and next, realistic pilot behavior. Realistic pilot behavior was defined by using a height error or lateral offset as an initial condition observing the correction maneuver, and making a judgment concerning the acceptability of the maximum attitude changes and rates of change.

What shall from here on be called the basic system (longitudinal), including the vehicle, pilot loop closures, and guidance and instrument indications was established so that in a correction maneuver from a 20 ft. height offset the vehicle would recover the predetermined path in approximately 4 sec with only a 3 ft. overshoot. (See Fig. 8.)

Also shown in Fig. 8 is the height error initial condition response when instantaneous height error rate information is also fed back to the collective pitch control through the pilot's time delay. Note the improved damping of the initial condition response. The correction maneuver showed a return to the desired glide path in 3 sec with virtually negligible overshoot. The root mean square height error, with the instantaneous height rate feedback, showed a reduction of 50% when compared to the basic system as shown in Fig. 10.

The pilot-aircraft system was next evaluated in a simulation of a "no gyro" GCA approach. The "no gyro" GCA is a term used in Army Aviation to signify a GCA approach in which the pilot is told only his direction of deviation from the desired glide path (i.e. above, below,

right or left of course). Simulation of the "no gyro" GCA system was accomplished by delaying height information to the pilot by 14 sec and by delaying height rate feedback to the collective (representing barometric height rate signals) by 0.4 sec. The correction maneuver with a 20 ft. height offset as the initial condition is shown in Fig. 9. Of particular interest in the "no gyro" run are the extremely small variations in motion variables other than the height, and the tendency to oscillatory instability, but the "no gyro" run demonstrated that with all of the feedback loops working, even rather poor height information (delayed 14 sec) can be used to obtain relatively satisfactory performance. This, of course, is not incompatible with actual experience. As an example, with a gust input representing rather severe atmospheric turbulence, the root mean square height error for the "no gyro" GCA system was only approximately 10 ft.

The influence of a pitch damper, which relieved the pilot of the necessity of supplying pitch damping, was investigated in connection with the "no gyro" GCA system, the basic system, and the instantaneous height rate system. While the damper was indeed beneficial in supplying damping of the pitching motions, evaluation of the root mean square height error showed that the effect on control of height, in each case, was negligible.

The comparison of root mean square height errors for a typical vertical gust input spectrum is shown in Fig. 10. (Horizontal gust inputs in the direction of flight were shown to have only very small effects.) Also illustrated in Fig. 10, in addition to the performance of the systems already discussed, are the performances of two systems substantially identical to the idealized "basic" system and the instantaneous height rate system except that height and height rate information are delayed 0.25 sec. This time delay represents the influence of the scanning delay in a scanning beam approach guidance subsystem which scans (in elevation) 4 times each sec. The Avionics Laboratory, U. S. Army, has such a scanning beam equipment under development. It may be seen that the influence of the scanning delay is very small. Lower scanning rates, however, would have a more pronounced effect.

By changing terms in the equations of motion which contain the flight path angle, γ, it was possible to investigate the effects on the basic system root mean square height error of changes in the geometric flight path angle. Path angles of -8 deg, -14 deg, -18 deg, and -24 deg were investigated and 12 different gust input spectra were used as each angle. The results, shown in Fig. 11, reveal that for each gust input spectrum the influence on the root mean square height error of varying the geometric glide path angle was entirely negligible. Confidence in this result was further heightened by varying, by ±20% from their initial value, the stability derivates X_w, M_u, Z_u, which are thought to be most sensitive to the rotor through-flow velocity. There was still only a negligible effect on the root mean square height error.

At the operating point of 40 knots, $X_u \doteq \partial D/\partial U \doteq 0$, and the vehicle is on a relatively flat portion of the power required curve. It is primarily for this reason that longitudinal gusts have so little effect on height errors. Substantial increments in X_u, both positive and negative, did not have any appreciable effect on the response of the closed-loop system. Nevertheless, the advantage of conducting actual operations at or near the speed for minimum power required should not be overlooked.

For very much the same reason that longitudinal gusts do not induce substantial height errors, it was found that longitudinal wind shears had very little effect. The model of the shear input which was used was a ramp function increasing at 1 ft per sec over a period of ten sec. (Although little seems to be known about wind shears in the lower portions of the atmosphere it would probably be generally conceded that this was a severe wind shear.) The effect of this shear was tested on both the basic system and the instantaneous height rate system. In neither case did the height deviation because of the wind shear exceed a value of 0.2 ft. This was considered to be a negligibly small effect.

The data collected in the evaluation of system performance by means of simulation may be used to make statements concerning the safety of operations into a proposed tactical heliport (Ref. 16). Figure 12 depicts the results of such calculations for the longitudinal case. Using a "no gyro" GCA approach and a glide slope of -8 deg it is seen that at a decision height of 150 ft. there is a 4.09% probability that the vehicle will be below the 7 deg line established as a minimum safety slope to the signal source. For the same case, however, there is only a 0.2% probability of the vehicle being below the line from signal source to the tope of an 80 ft. obstacle located 800 ft. from the signal source. The corresponding probabilities for the basic system are 0.001% and 1×10^{-12}%. The comparison of these figures with the ones for the "no gyro" GCA show the improvement to be expected from the use of an improved guidance subsystem. A glide slope of 10° 40' with "no gyro" GCA would provide for arrival at decision height directly over the 80 ft. obstacle with a probability of very near zero of actually hitting the obstacle, and the same thing is true only much more so in connection with improved approach guidance subsystems.

B. Lateral-Directional Case

In the lateral plane of motion the pilot-vehicle systems were established with the same components comprising the longitudinal systems, i.e. vehicle, pilot loop closures, and guidance and instrument indications. Again pilot loop gains were established using the criteria of system stability and realistic pilot behavior. Realistic pilot behavior was determined by establishing an initial 500' offset error from the desired course and observing the correction maneuver to the course. In addition to the time delays of the pilot, all cases in the lateral plane of motion which were studied had a 0.25 sec time delay superposed on the system to represent the influence of the scanning delay in a scanning

beam approach guidance subsystem which scans (in azimuth) 4 times each second.

The first system investigated in the lateral case was a heading command system in which the distance of deviation from the desired course provided the command input. Integration in the forward loop of this system satisfies the requirement of maintaining course in the presence of a steady crosswind (Ref. 16). What shall henceforth be referred to as the integral-control system was a system containing, in addition to the feedback loops shown in Fig. 7, the addition of course deviation, ΔD, integration as a feedback to the lateral cyclic control. The loop gains established for this system were such that with the initial 500 ft. offset from the course, the correction maneuver of the pilot-vehicle system would be as shown in Fig. 13. Here the maximum bank angle for the correction maneuver was approximately 6° and the maximum heading change was approximately 10°. The correction maneuver itself showed a return to the course in 22 sec with a slight tendency toward a very low frequency oscillatory instability.

The next system to be considered was a simulation of the "no gyro" GCA system in the lateral plane of motion. For this simulation the same pilot loop closures were used as in the integral control system. However, in the "no gyro" GCA simulation course deviation information to the pilot was delayed 10 sec. The motion variables of interest in the correction maneuver executed with the "no gyro" system showed a shallower bank angle and smaller heading change in connection with a slower return to the desired cause than with the integral-control system. Nevertheless, the correction maneuver showed that even with relatively poor course deviation information (delayed 10 sec) it was a workable system. This again is not incompatible with actual exerpience.

Also of interest in the lateral case was a bank angle command system. In this third type of lateral system the heading information was not fed back, but instead was replaced by course offset distance and closure rate feedback as the command input for bank angle control. This system, called the beam rate system, was established with appropriate pilot gains so that the correction maneuver was a return to the desired course in approximately only 16 sec with virturally no course overshoot, At the same time the motion variables, bank angle, heading, and yaw rate were maintained within reasonable limits.

A comparison of root mean square lateral deviation errors for a typical horizontal gust input spectrum representing moderately severe atmospheric turbulence is shown in Fig. 14. For each system the rms lateral deviation error was considered reasonable in terms of actual practice. Of particular interest is the reduction by 30% of the rms lateral deviation error of the beam rate system when compared to the integral control system. Although the improvement obtained by a beam rate feedback is not as great as in the longitudinal case, the important beneficial effect should possibly be considered in specifying receiver characteristics for new helicopter approach guidance systems.

Side wind shear effects were also investigated for each system

in the lateral case. The horizontal wind shear model used was the same as for the longitudinal case, i.e. a ramp input increasing at 1 ft per sec for 10 sec. Recall that this shear may be considered to be severe. For each case the lateral deviation error at the conclusion of the wind shear input was on the order of 15 ft. Even with the low frequency and low damping characteristic of the lateral systems these deviation errors were still considered to be relatively unimportant. The errors because of the shear were of the same order of magnitude as the side gust induced components of error for the systems with scanning beam guidance. A displacement from the desired course at the decision height of even thirty feet (which might represent the combined effect of severe gusts and shears) would not be likely to have any very serious effects.

With respect to motion in the horizontal plane, Fig. 15 shows the effect of lateral deviation error because of gusts, at decision height, for the integral-control lateral-directional control system. For purposes of discussion we might assume a localizer beam width of 3°. Placing the localizer signal source at the far end of the heliport from the direction of approach increases the effective coverage and "flyability" of the localizer. With an approach made at -8° glide slope, the vehicle arrives at the 150 ft. decision height approximately 2100 ft. from the localizer signal source. At this point, with the integral-control system, there is a 0.02% probability that the vehicle will be outside the (assumed) limit of the beam. Being outside the beam would correspond to a full-scale needle deflection in an arrangement where the localizer beam gave displacement as in the conventional ILS system. The same system gives a 0.12% probability of being outside the beam when the approach is made at -10° 40' glide slope. As the glide slope angle is increased (negatively), and the distance from the signal source at decision height is thereby decreased, the probabilities of being outside the beam will then correspondingly increase. These facts indicate that it is probably desirable to use a wider beam. The integral-control heading command system seems plausible for use even with a localizer beam 3° in width.

The beam rate bank angle command system has lower probabilities of being outside of the beam than the integral control system. For the approach at -8° glide slope the beam rate system has a negligibly small probability of being outside of the beam and this "tight" system is to be recommended.

In the horizontal plane the "no gyro" GCA system can be discussed without any confinement to a given beam width. For a "no gyro" GCA appraoch at -8° glide slope the vehicle would arrive at decision height 2100 ft. from the approach end of the heliport and with a .0026% probability of being outside a distance of 133.5 ft. from the desired approach course. The value of 133.5 ft. corresponds to three standard deviations of the gust induced lateral deviation error distribution. Even if the vehicle were 133.5 ft. from course, however, upon arrival at the decision height on the same heading as the course, a turn of only 7° would put the vehicle on an inbound course to the heliport. For a

"no gyro" GCA system approach at -10° 40' glide slope there is the same .0026% probability of being 133.5 ft. from the course. Upon arrival at decision height a 9.6° turn would be required to establish an inbound course to the approach end of the heliport. These are comparatively mild maneuvers and tend to establish the fact that gust or shear induced lateral deviation errors are not so serious a limitation in helicopter operations as in fixed wing aircraft operations because it is not necessary to line the helicopter flight path up with a runway.

VII. IMPLICATIONS FOR COCKPIT DESIGN

The results of this system analysis of control of helicopters on instrument low approach, suggest, but do not demonstrate, certain implications for cockpit design.

1. Display-Control Association. Since the best means for the control of airspeed and the decoupling of height control was found to involve the feedback of pitch angle error and speed error to the longitudinal cyclic pitch control, it would seem that, contrary to the practice in fixed-wing aircraft, a speed error indication should be closely associated with display of pitch angle, while the height error (fed to the collective pitch control) should be spearated from these two in the display.

2. Use of Instantanecus Hight-Rate and Lateral Beam Rate. The powerful advantage of instantaneous height rate and lateral beam rate in the reduction of dynamic errors in following the approach path commends a flight director instrument combining vertical displacement and height-rate information and lateral displacement, beam rate, and bank angle to our attention. The substantially instantaneous height rate information might possibly be derived from the radio guidance, or alternatively may be computed by integrating the output of an airborne vertical accelerometer corrected to the true vertical and combined in a complementary filter with barometric rate of climb/descent information (Ref. 18).

3. Vertical and Horizontal Situation Displays. If the height and height rate information are combined in a director instrument, a new vertical situation display is going to be required. One version of such a display, The Flight Profile Indicator, has been synthesized by Mr. William Austin, Link Division, General Precision, Inc. in connection with a U. S. Air Force program (Ref. 18). The Flight Indicator shows the position of the aircraft with respect to the glide slope and the runway as well as showing the magnitude and direction of the aircraft's velocity vector. Much, if not all the information required for this display, can be derived from an improved ground based guidance subsystem. It seems that a conventional horizontal situation display would be suitable.

4. Supplementary Automatic Control. It did not appear, from the results of our study that, on approach, there was any performance advantage to be gained by the use of automatic control, notably a pitch

damper. This, of course, is not to say that the pilot's comfort, convenience, and stress level might not be ameliorated by performing some functions automatically.

A suggested evolutionary panel arrangement for instrument low approach in helicopters is presented as Fig. 16.

VIII. CONCLUSIONS

The theoretical analyses and simulation studies conducted at Princeton University under the PPAAR Task: "System Study of Low Visibility Approach and Landing" have shown that relatively steep angle (12°) approaches to low decision heights (150 ft.) can be made, on instruments, in helicopters equipped with available instrumentation and provided with a suitable source of guidance information.

The general features of a typical (voice link) GCA approach were reproduced in the simulation, and the 12° glide slope recommended after flight tests at Ft. Rucker, Alabama, was shown to correspond to an operating point (airspeed and rate of descent) near the speed for minimum power required, above the region of roughness (which can extend as high as 30 knots), and at a rate of descent only about half of a typical rate of descent in autorotation. (For the same flight condition with respect to the air mass, the glide slope would be in excell of 20° when flying into a 20 knot headwind.) Investigation showed, over a wide range of typical values (-8° to -24°), that there was no appreciable effect on the closed loop dynamics of changes in the inertial terms in the equations of motion which are functions of the flight path angle. Stability derivatives thought possibly to be sensitive to rotor through flow velocity were also varied in the simulation with only minute effects on the closed loop dynamics. These facts, taken together, indicate that up to 24°, at least, the steepness of helicopter approach paths is not limited by considerations of stability and control as long as the airspeed is approximately the speed for minimum power required and the rate of descent does not approach the rate of descent in autorotation. (Other considerations which might limit the steepness of approaches, such as the time available to make a transition to visual flight upon reaching the decision height, or forward visibility through the cockpit windshield were not amenable to analysis by the methods used in this study.)

With the performance of the human pilot taken into account via a describing function model and considering the guidance data rate actually proposed to be employed, two very successful loop topologies were identified for each of the longitudinal and lateral cases. In both cases the system may be made to work at a level which shows a considerable improvement over the standard GCA without the use of radio beam rate. In both cases a further improvement can be achieved through the use of derived rate from the vertical scanning beam and the azimuth scanning beam. The biggest improvement is with the use of derived rate from the vertical scanning beam.

The influence of a pitch damper on the performance of the longitudinal closed loop control and guidance system was found to be very samll. For this reason roll and yaw dampers were not investigated.

Errors induced by random atmospheric turbulence were the dominant errors in the longitudinal case and were comparable to errors induced by wind shear in the lateral case. Errors induced by inaccuracies in the guidance were thought, but were not shown to be, much smaller.

For manual control of instrument low approach in helicopters at least the following signals should be displayed to the pilot for flight control:

- pitch attitude
- airspeed
- height error (beam displacement)
- bank angle
- heading angle
- lateral beam displacement
- lateral acceleration (slip)
- yaw rate (turn)

A successful automatic approach system could be mechanized with the same signals.

Potential improvements could be realized, especially if flight director type instruments were employed, by adding pitch rate, instantaneous vertical speed or vertical beam rate, and azimuth beam rate. The use of these signals would also improve an automatic system.

References

1. Dukes, T. A., E. J. Durbin, D. Graham, F. H. Schmitz, and E. G. Sharkoff, The Princeton Pennsylvania Army Avionics Research Program Annual Report No. 1, prepared for the period 1 June 1966 to 30 May 1967, Contract No. DA28-043 AMC-02412 (E) for the U. S. Army Electronics Command, Ft. Monmouth, N. J. Technical Report ECOM-0241-1 October 1967.

2. Roberts, L. D., An Analysis of Helicopter Control in Landing Approach, MSE Thesis, Department of Aerospace and Mechanical Sciences, Princeton University, December 1967.

3. Graham, D., and N. K. Nydegger, "A Systems Analysis of Instrument for Helicopters," paper presented at the Avionics Symposium, Ft. Monmouth, N. J., 5-8 March 1968.

4. Nydegger, N. K., A Systems Analysis of Instrument Low Approaches in Helicopters, MSE Thesis, Department of Aerospace and Mechanical Sciences, Princeton University, May, 1968.

5. McRuer, D., D. Graham, E. Krendel, and W. Reisener, Human Pilot Dynamics in Compensatory Systems, AFFDL-TR-65-15, WPAFB, Ohio, July 1965.

6. McRuer, D., D. Graham, and E. Krendel, "Manual Control of Single-Loop Systems, Parts I and II," J. of the Franklin Inst., Vol. 283, no. 1 and 2, January and February 1967.

7. McRuer, D., H. Jex, W. Clement, and D. Graham, Development of a System Analysis Theory of Manual Control Displays, STI TR 163-1, forthcoming report for the Office of Naval Research, Department of the Navy, Washington, D. C.

8. McRuer, D. T., Unified Analysis of Linear Feedback Systems, ASD TR 61-118, WPAFB, Ohio, July 1961.

9. McRuer, D. T., I. L. Ashkenas, and H. R. Pass, Analysis of Multiloop Vehicular Control Systems, ASD TR 62-1014, WPAFB, Ohio, March 1964.

10. Etkin, B., Dynamics of Flight, John Wiley and Sons, Inc., N. Y., 1959.

11. Seckel, E., Stability and Control of Airplanes and Helicopters, Academic Press, New York, 1964.

12. Pritchard, F., A Statistical Model of Atmospheric Turbulence and a Review of the Assumptions Necessary for Its Use, paper presented at the AGARD Specialists' Meeting on Stability and Control, 20-23 September 1966.

13. Benedict, T. R., and V. C. Rideout, "Error Determination for Optimum Predicting Filters," Proc. National Electronics Conference, Vol. 13, 1957.

14. Etkin, B., A Simple Method for the Analogue Computation of the Mean-Square Response of Airplanes to Atmospheric Turbulence, Univ. of Toronto, Institute of Aerophysics, UTIA Technical Note No. 32, January 1960.

15. Magdaleno, R., and J. Wolkovitch, Performance Criteria for Linear Constant-Coefficient Systems with Random Inputs, ASD TDR-62-470, Wright-Patterson AFB, Ohio, January 1963.

16. Saganowich, J. T., Factors Affecting the Development of Helicopter Landing Systems, Proc. of the PPAAR Symposium, The Franklin Institute, June, 1967.

17. Blakelock, J. H., Automatic Control of Aircraft and Missiles, John Wiley and Sons, Inc., New York, 1965.

18. Knemeyer, S., and G. L. Yingling, Results of the USAF Pilot Factors Program as They Apply to Flight Safety, paper presented at the 12th Annual Business Aircraft Safety Seminar, 15-18 May 1967, Washington, D. C., Air Force Flight Dynamics Laboratory, WPAFB, Ohio.

Glossary

D	Drag (lbs)
D	Lateral deviation (convenient units which may be linear or angular)
e	Base of natural logarithms = 2.718
h	Height (ft)
h_e	Height error (ft)
j	$= \sqrt{-1}$
K	Gain constant
K_p	Pilot's gain
L	Scale length of atmospheric turbulence (ft)
M_u	$= \frac{1}{I_y} \frac{\partial M}{\partial u}$, Pitching moment due to longitudinal velocity
r	Yawing velocity, (deg/sec)
r(t)	Transient analog of gust input spectrum
s	$= \sigma + j\omega$, Laplace transform variable
T_E	Equalization (lead) time constant (sec)
t	Time (sec)
U	Longitudinal velocity (ft/sec)
U_o	Trimmed longitudinal velocity (ft/sec)
u	Perturbation longitudinal velocity (ft/sec)
w	Plunging velocity (ft/sec)
X_w	$= \frac{1}{m} \frac{\partial X}{\partial w}$, Longitudinal force due to plunging velocity
x	Number of normalized standard deviations (lbs)
$Y_p(s)$	Pilot's describing function
Z_u	$= \frac{1}{m} \frac{\partial Z}{\partial u}$, Normal force due to longitudinal velocity (lbs)

β	Angle of sideslip
γ	Flight path angle (deg)
δ_a	Rolling moment control deflection
δ_e	Pitching moment control deflection
δ_r	Yawing moment control deflection
θ	Pitch angle
σ	Standard deviation
τ, τ_{eff}	Time delay, effective time delay (sec)
φ	Bank angle
Ψ	Heading angle
ω	Frequency (rad/sec), break frequency
rms error	$\equiv \left[\frac{1}{T}\int_0^T \text{(actual value - nominal value)}^2\, dt\right]^{1/2}$

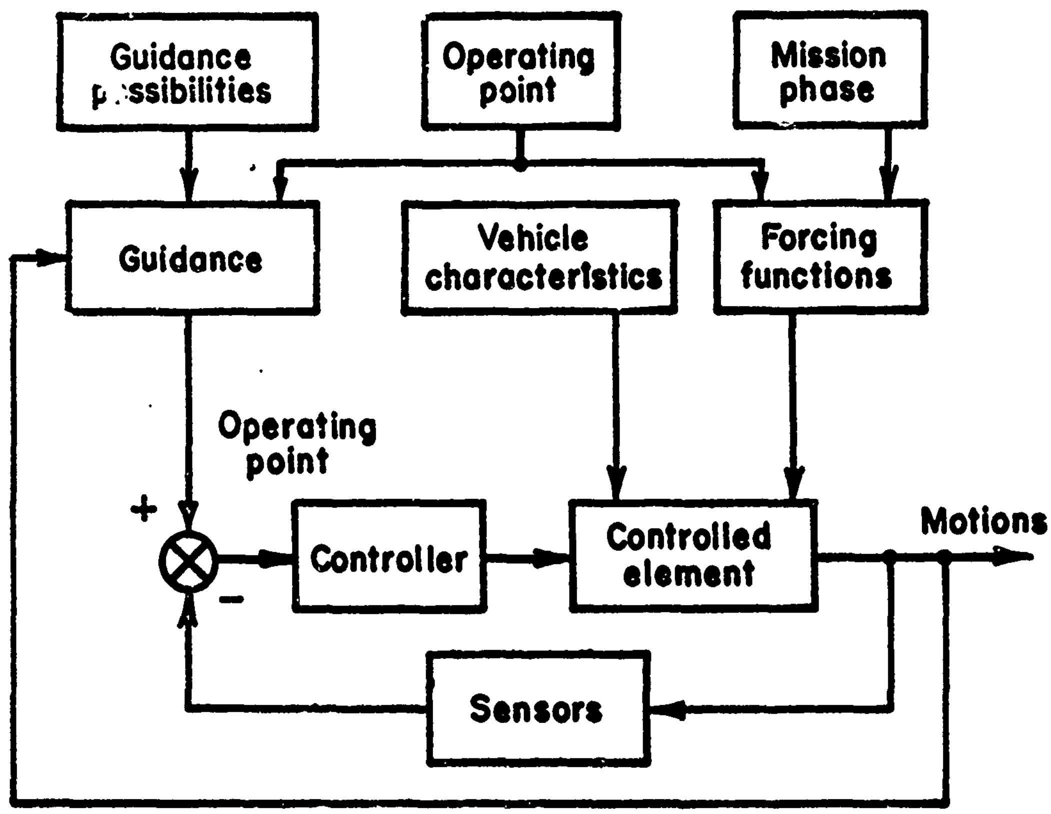


FIGURE I. EVOLUTION OF CONTROL AND GUIDANCE SYSTEM REQUIREMENTS

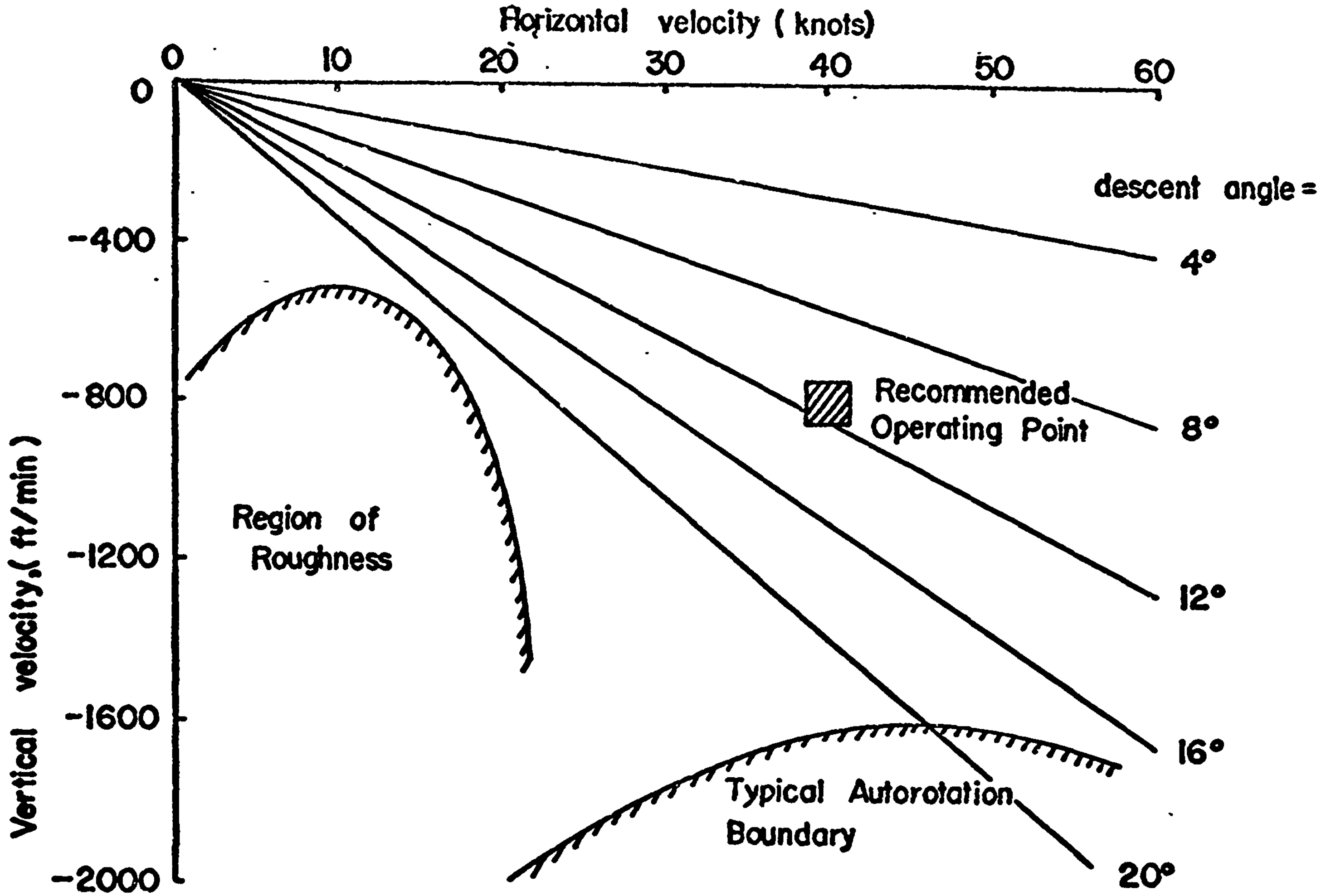


Fig. 2: Performance of Helicopters in Descent

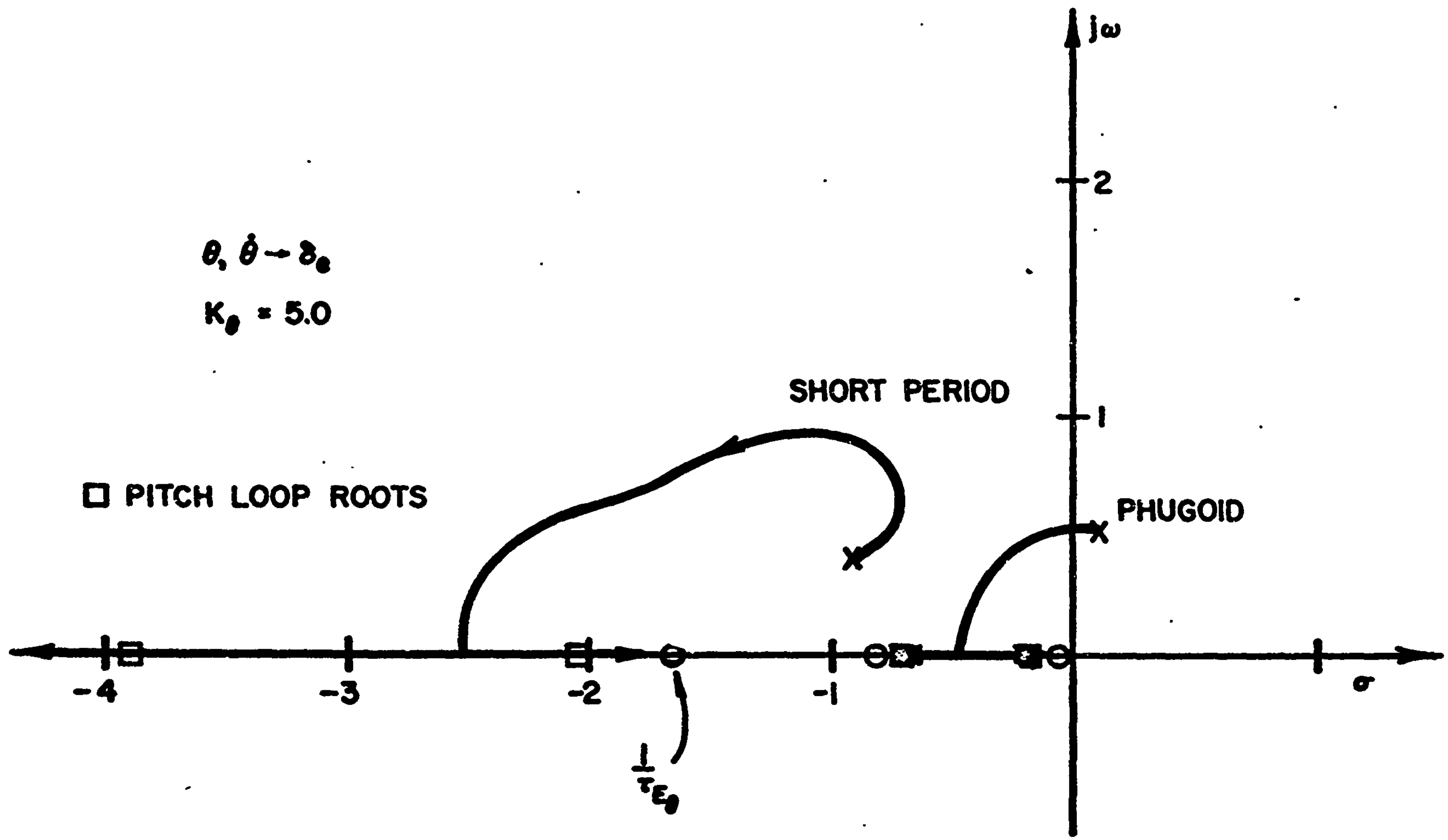


Figure 3. Pitch Angle and Rate Feedback to Longitudinal Moment Control

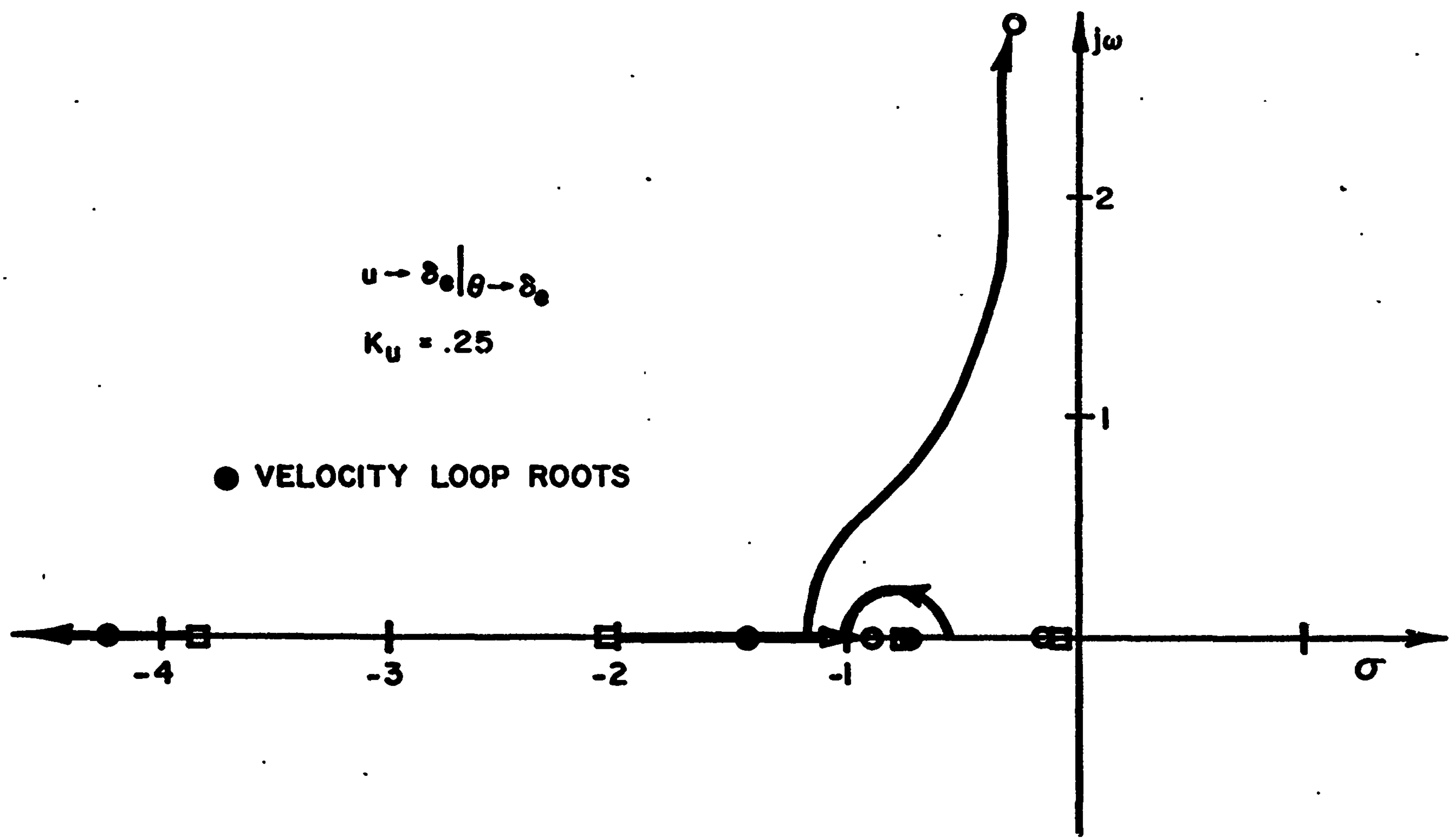


Figure 4. Velocity Feedback to Longitudinal Moment Control

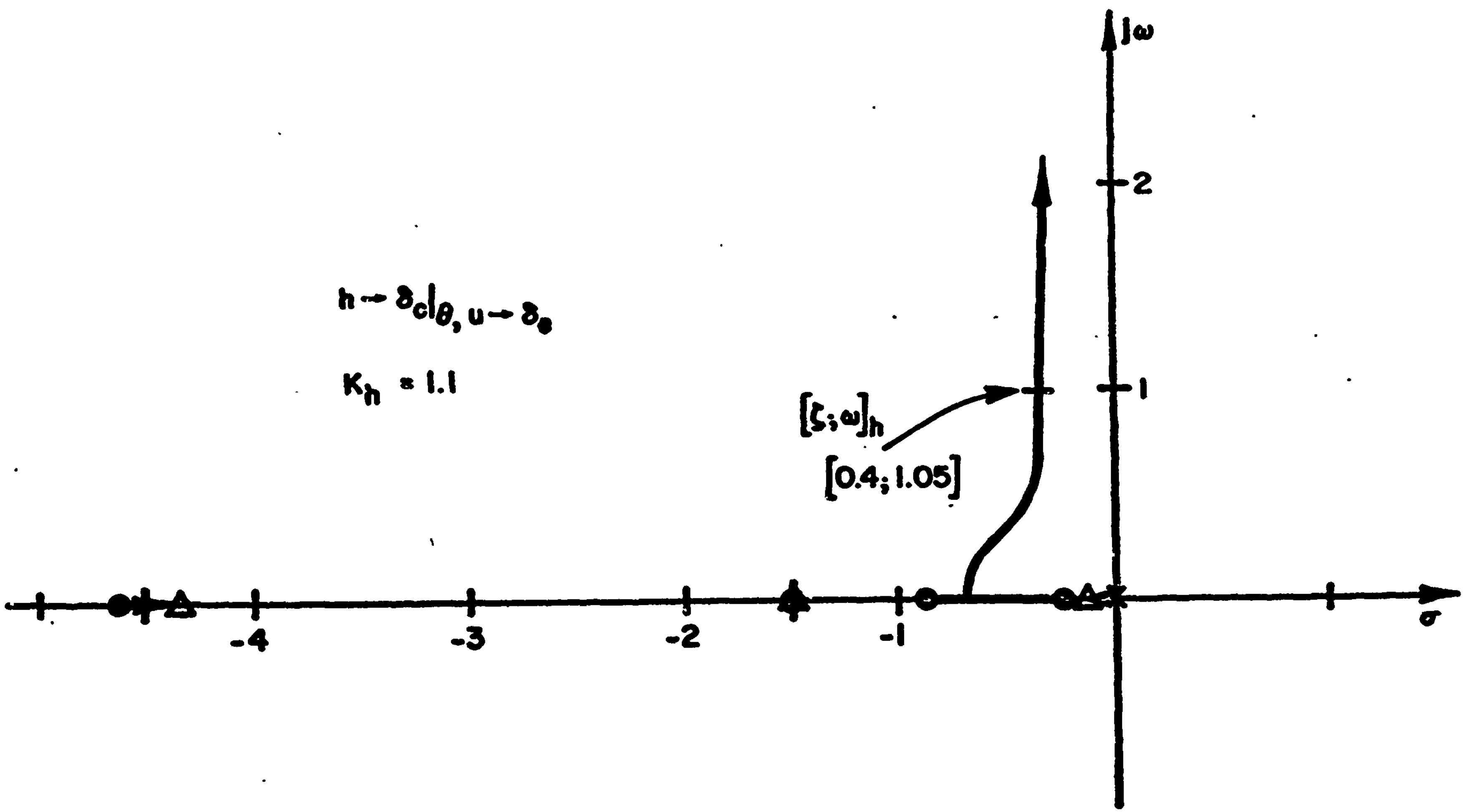


Figure 5. Height Feedback to Collective Pitch Control

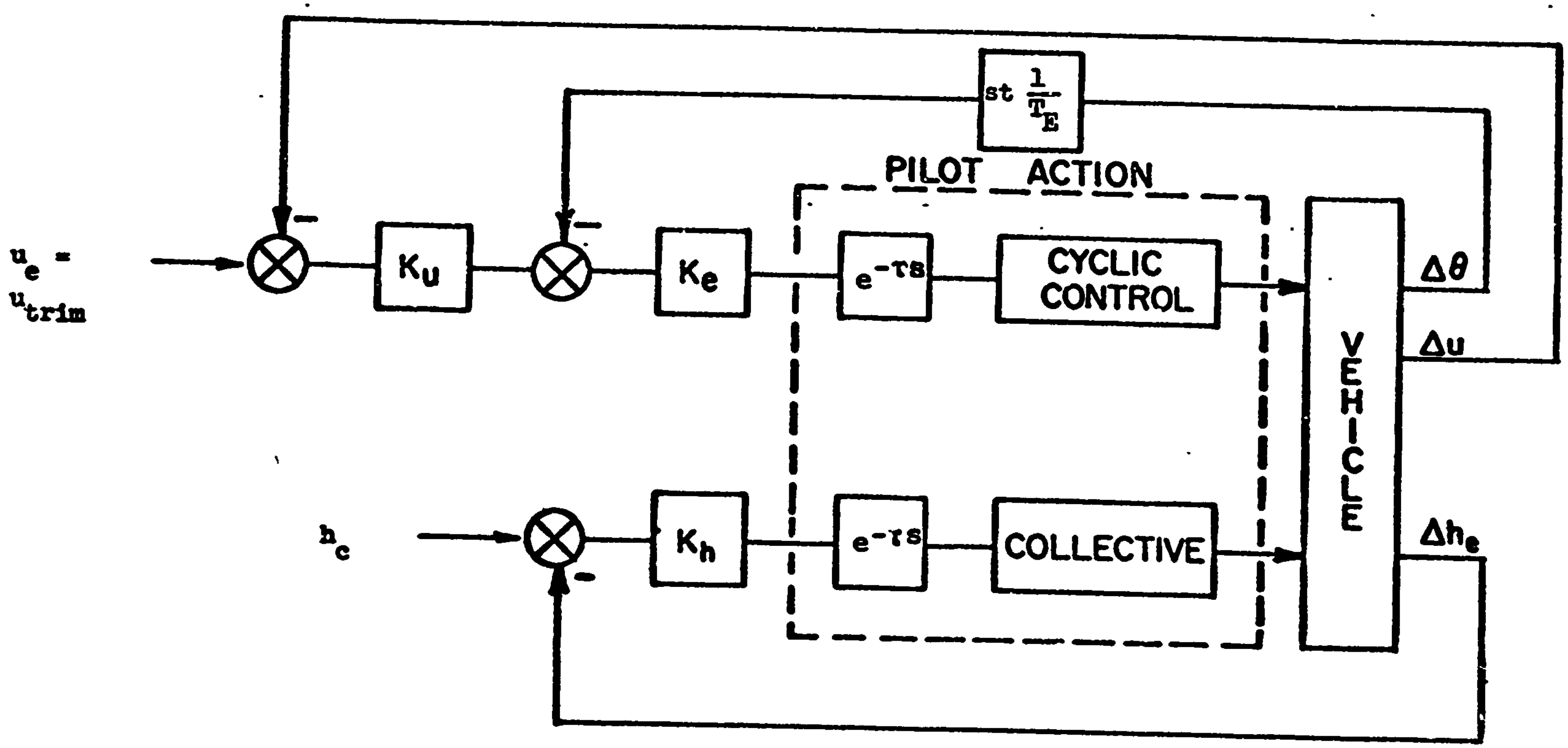


Figure 6. Block Diagram of the Basic System (Longitudinal Motion)

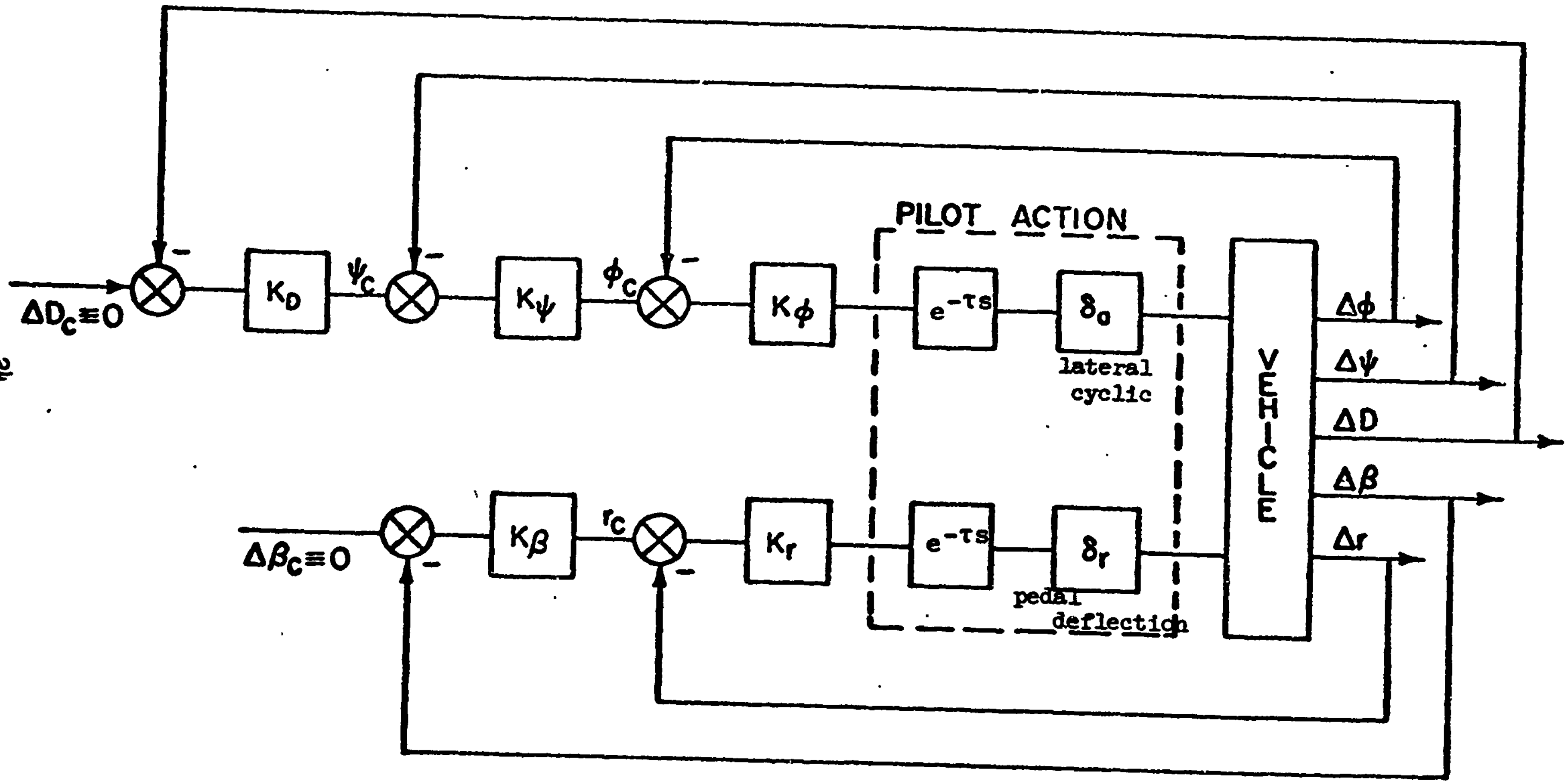


Figure 7. Block Diagram of the Basic System (Lateral Motion)

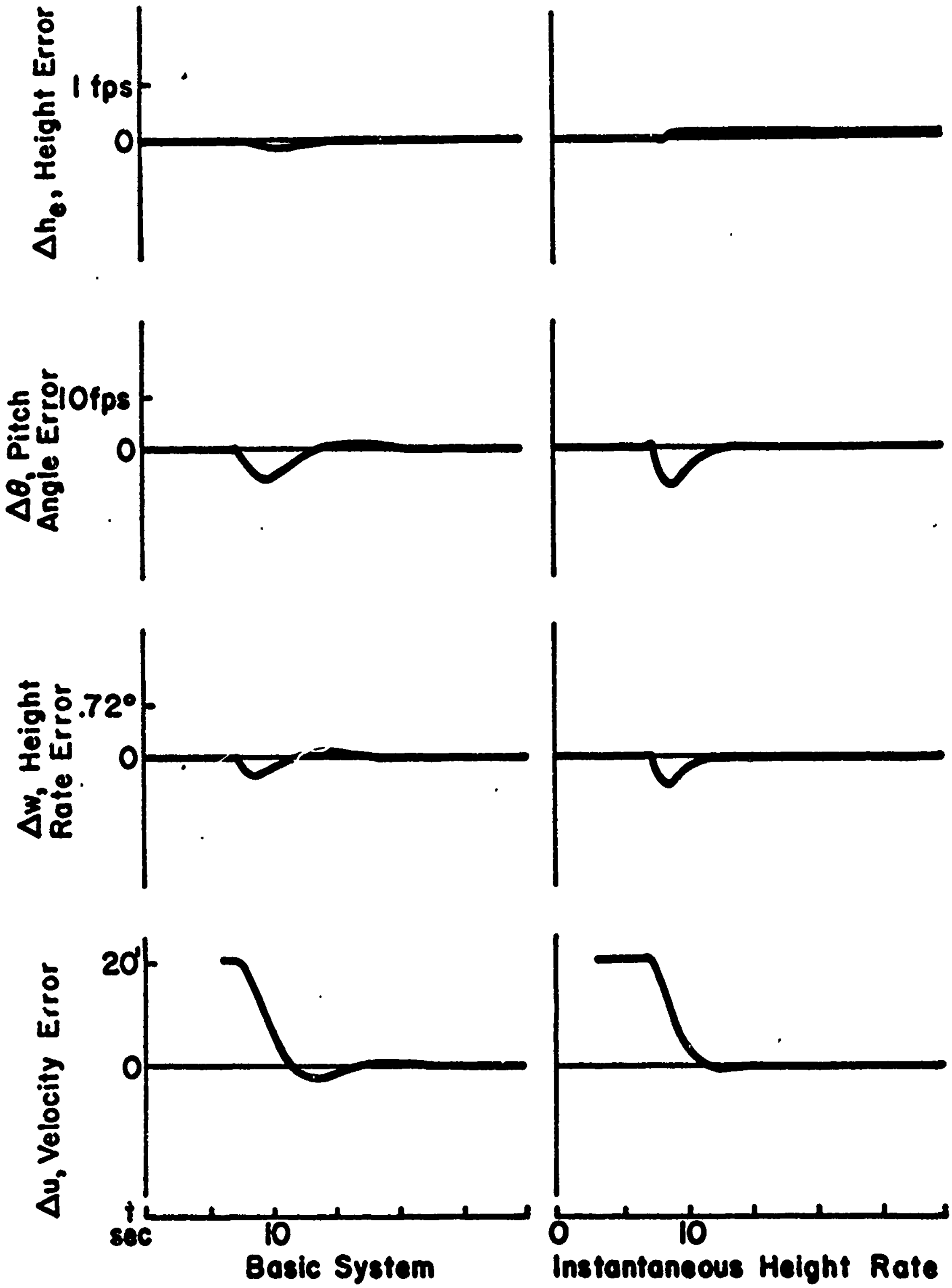


Figure 8. Height Error, Initial Condition Response with no Disturbances (Basic System)

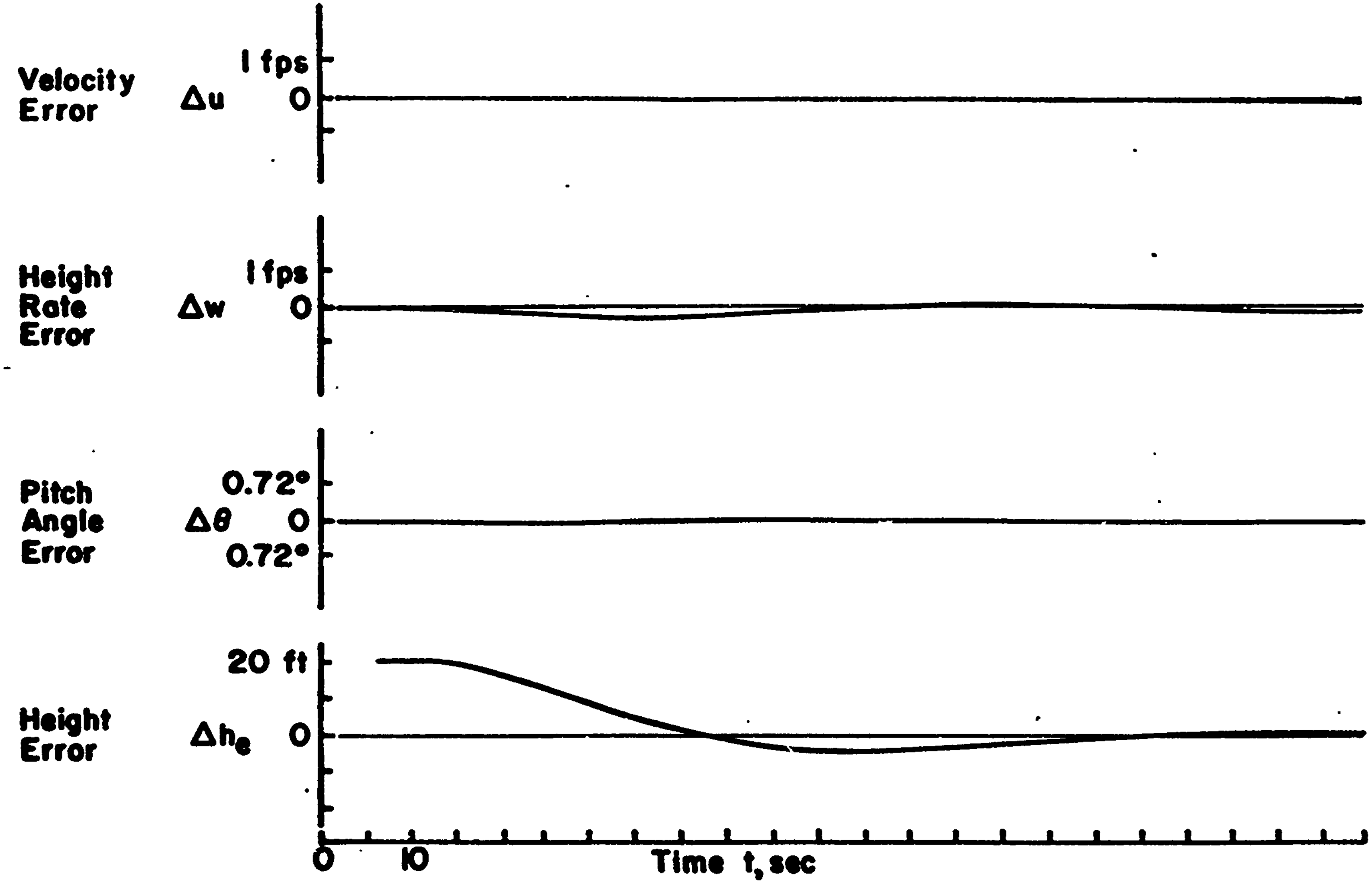
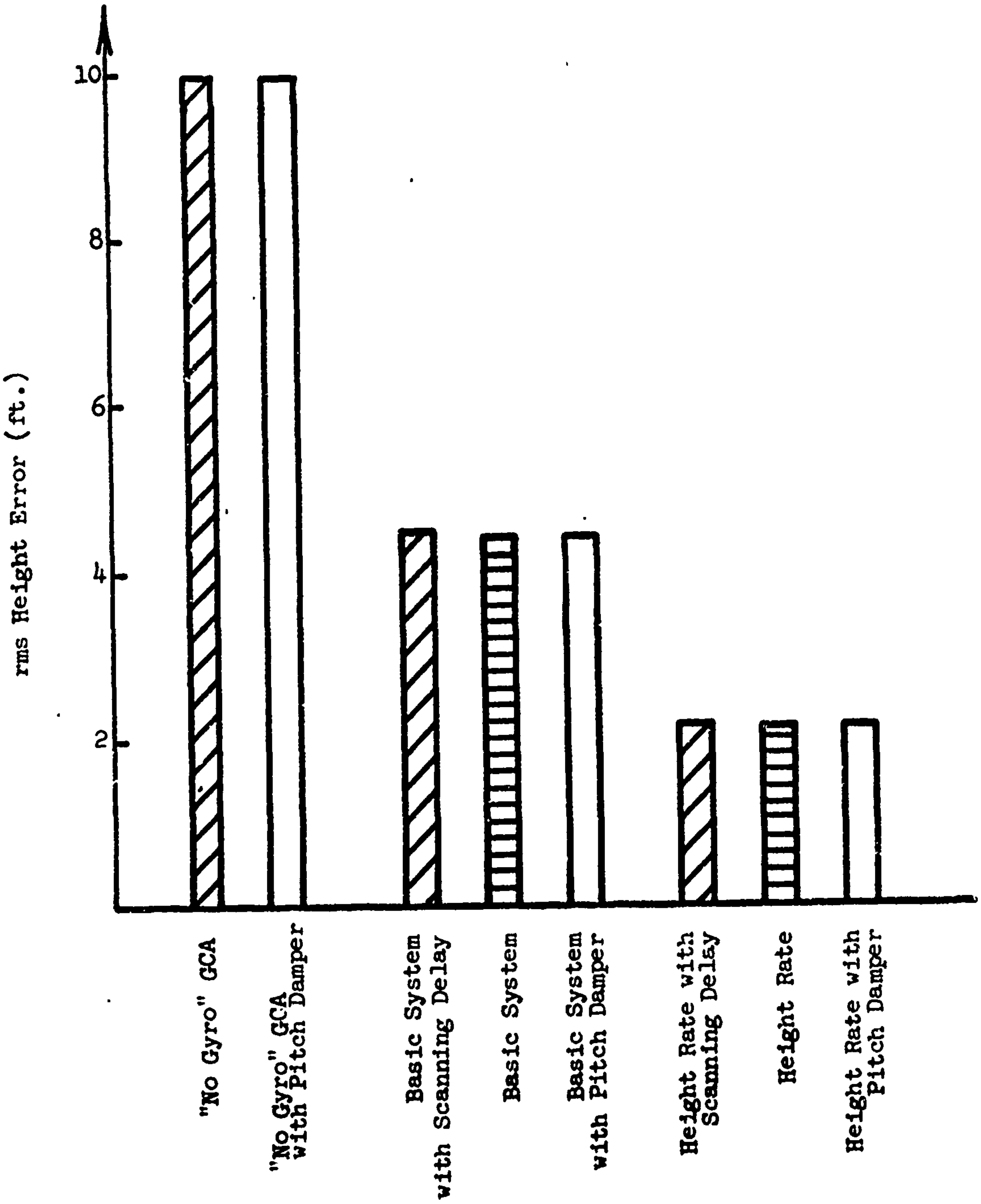


Figure 9. Height Error, Initial Condition Response with no Disturbances ("No Gyro", GCA)



Glide Path Angle $\gamma = -14^{\circ}$

Gust input $\sigma = 11.5, \frac{1}{\omega} = 0.108$

Figure 10 rms Height Errors

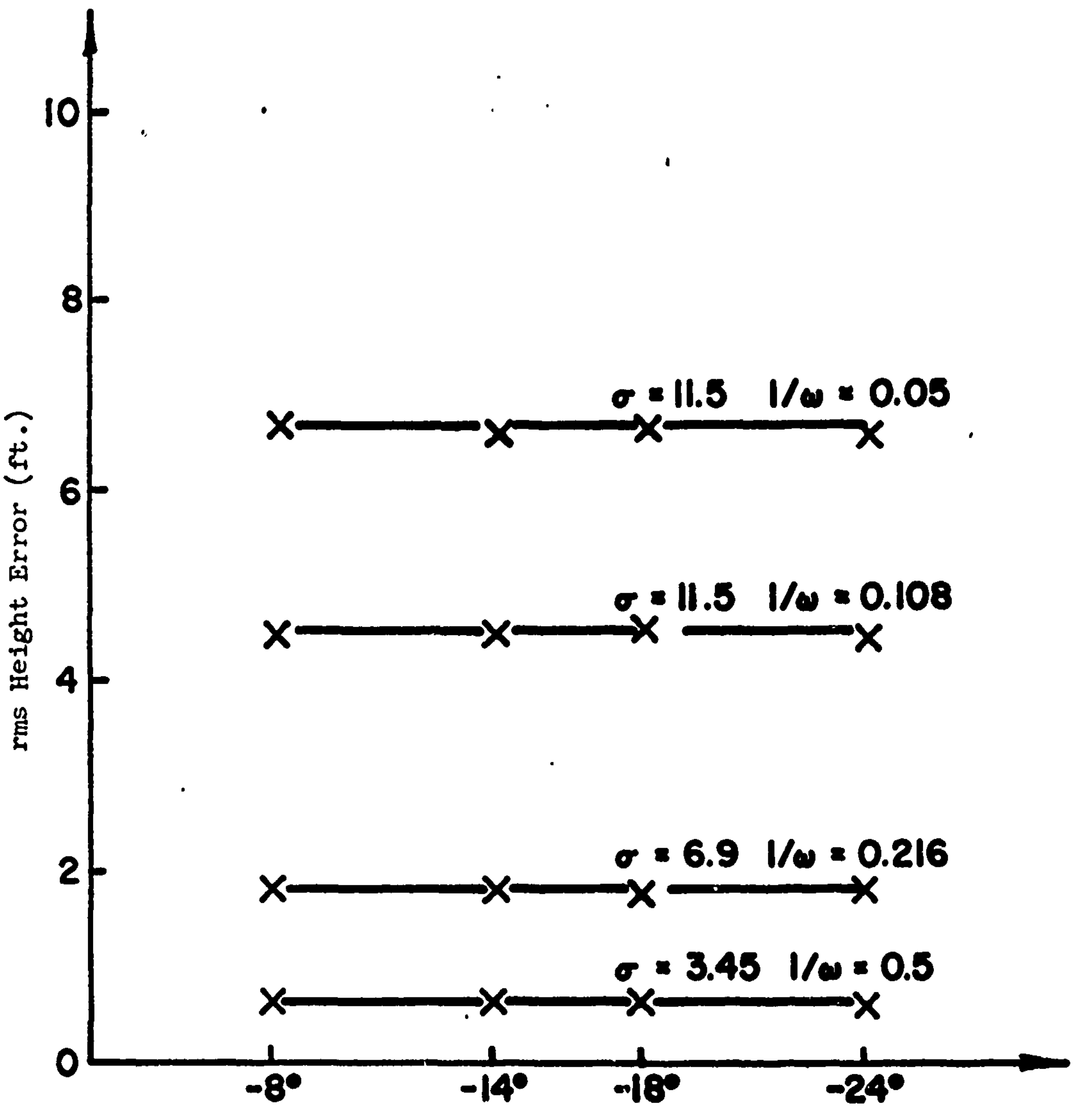


Figure 11. Glide Path Angle vs. rms Height Error for The Basic System

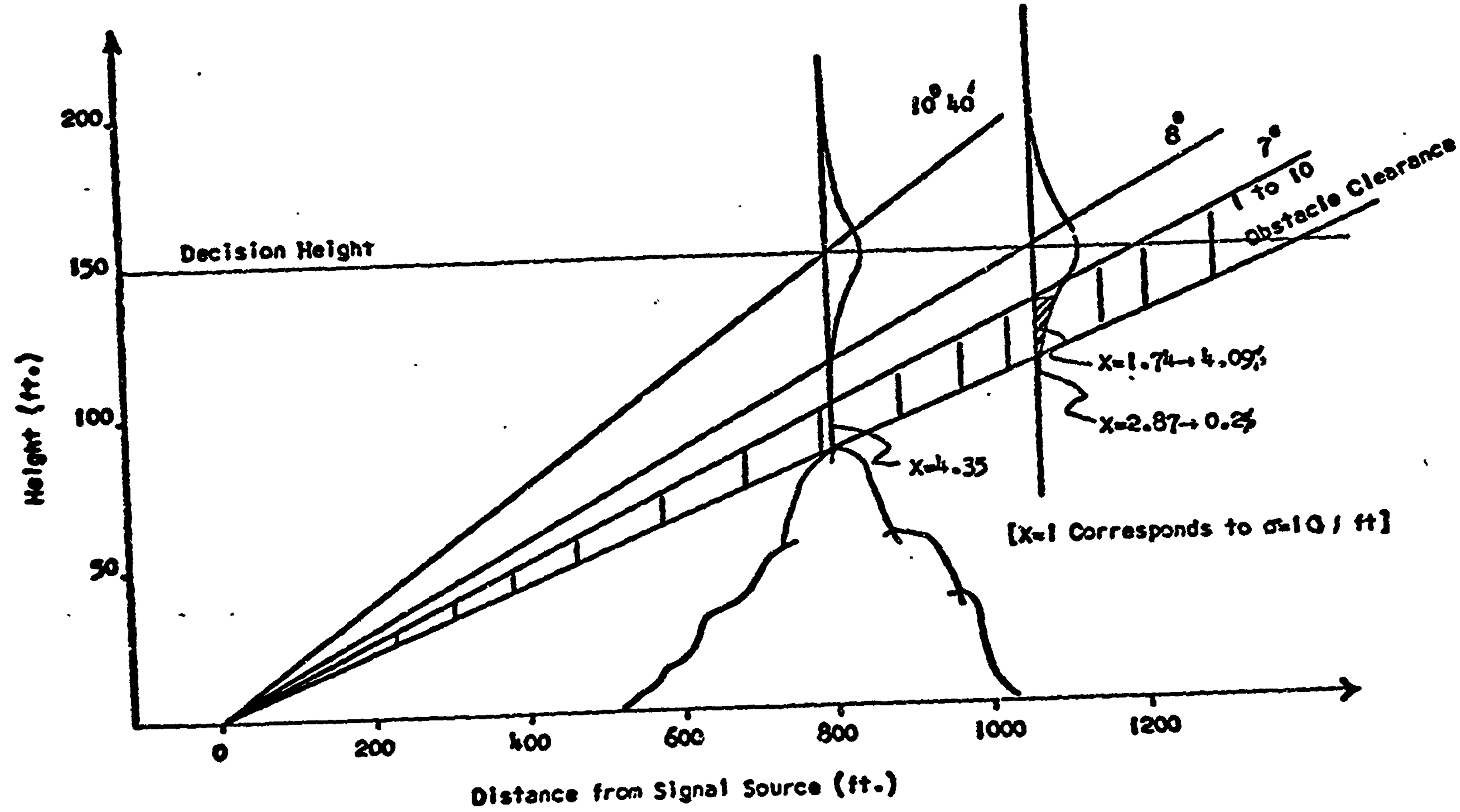


Figure 12. Effect of rms Height Error at Decision Height
"No Gyro" GCA

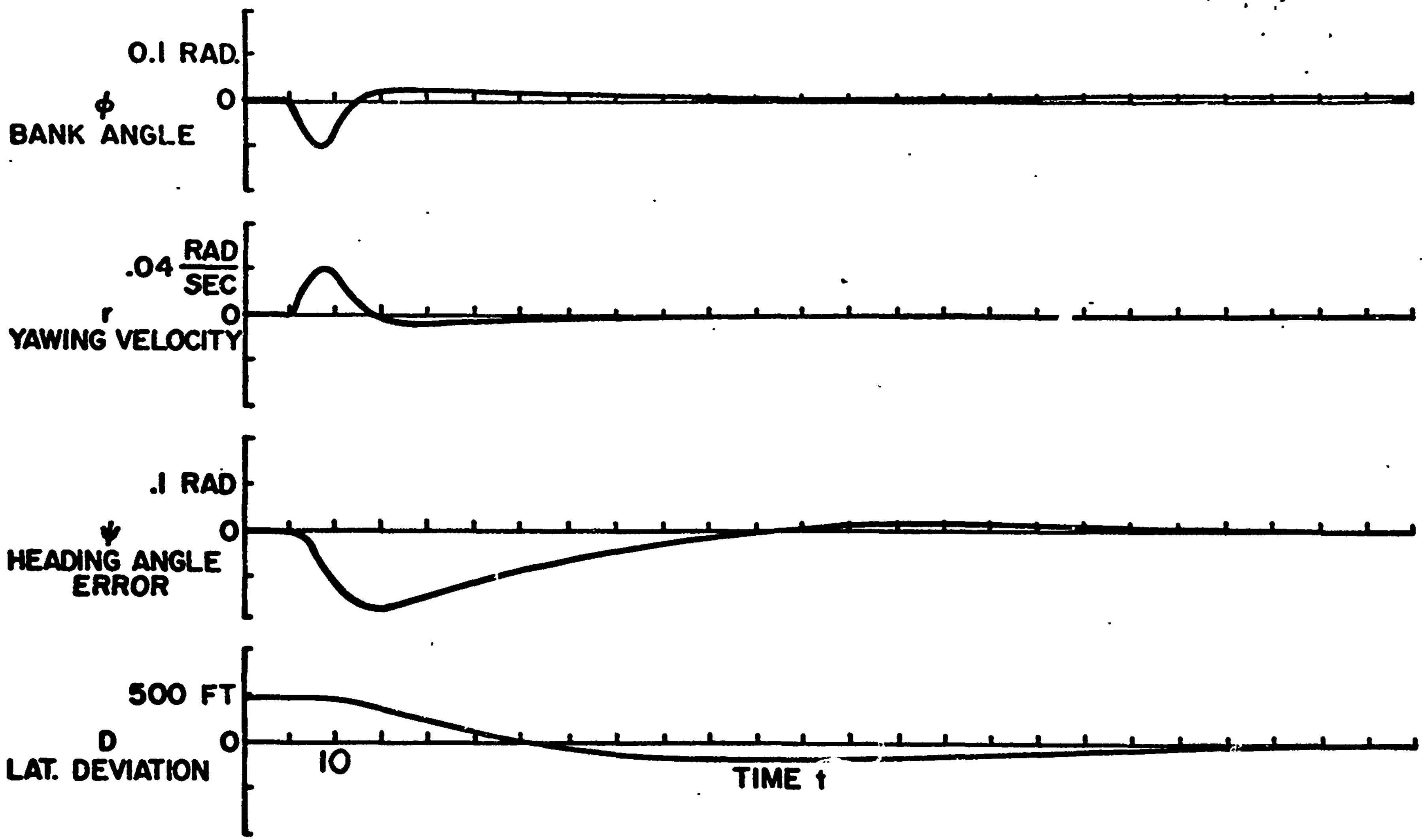
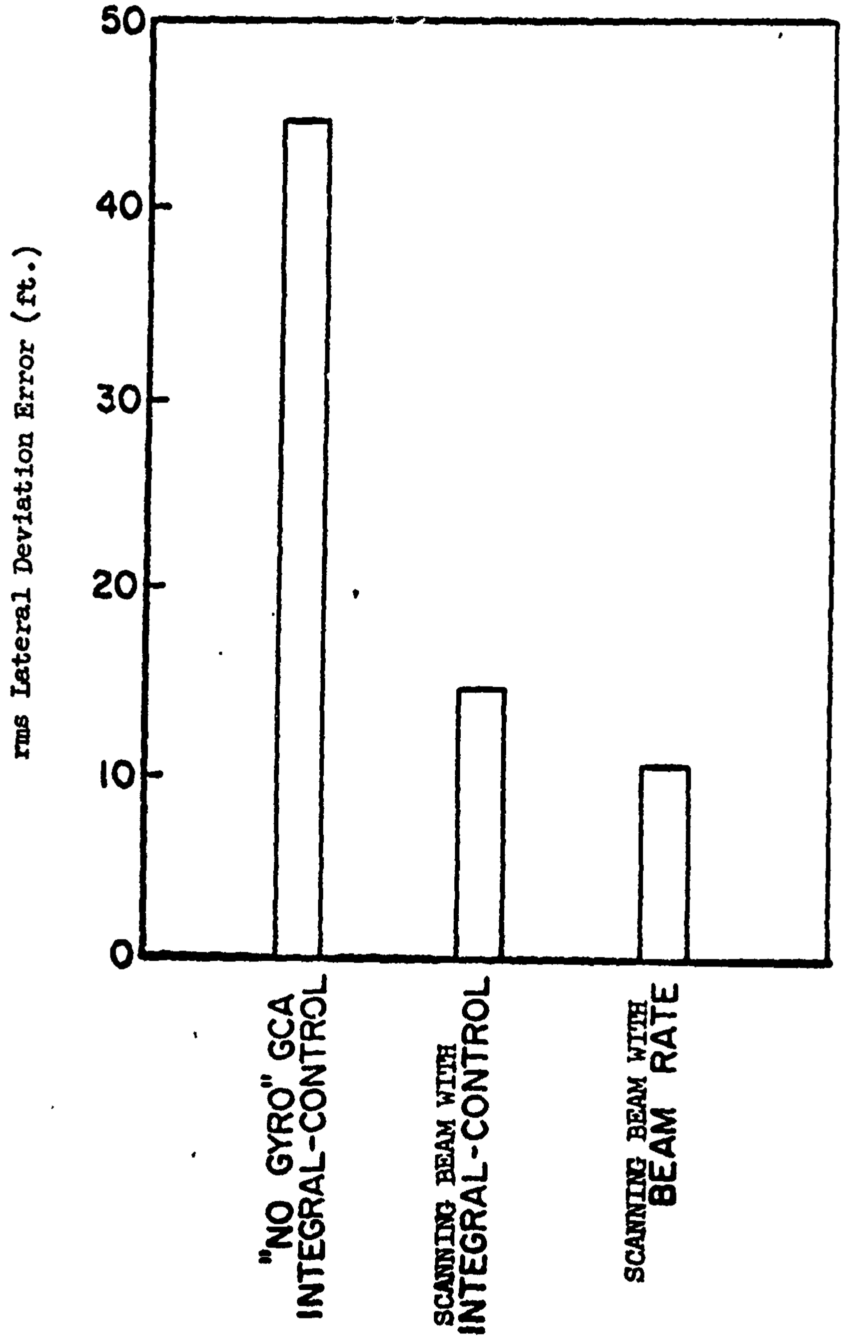


Figure 13. Course Error, Initial Condition Response, Integral-Control, with no Disturbances



GUST INPUT $\sigma = 11.5, \ \frac{1}{\omega} = 0.108$

Figure 14 Comparison of rms Lateral Deviation Errors

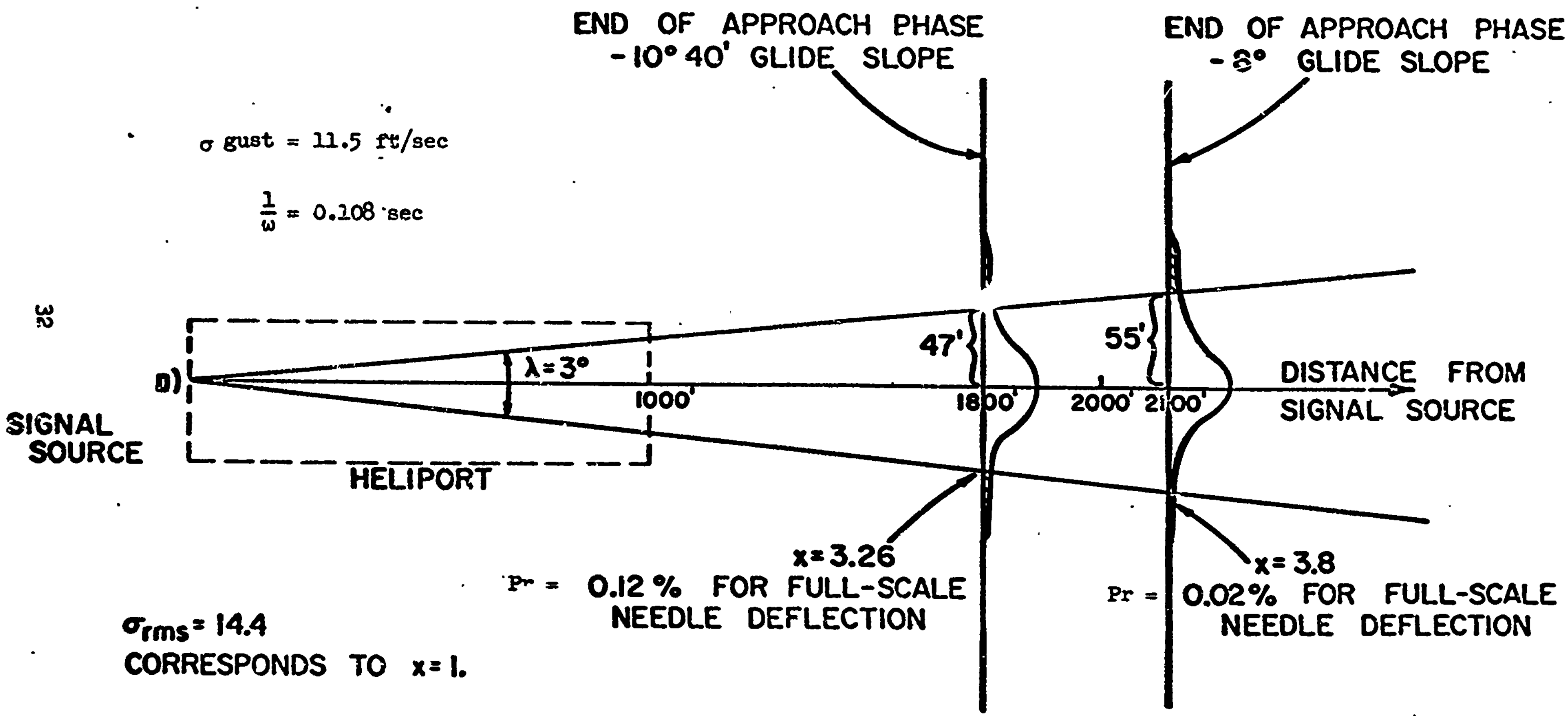


Figure 15 Effect of rms Lateral Deviation Error Because of Gusts at Decision Height -- Integral Control System

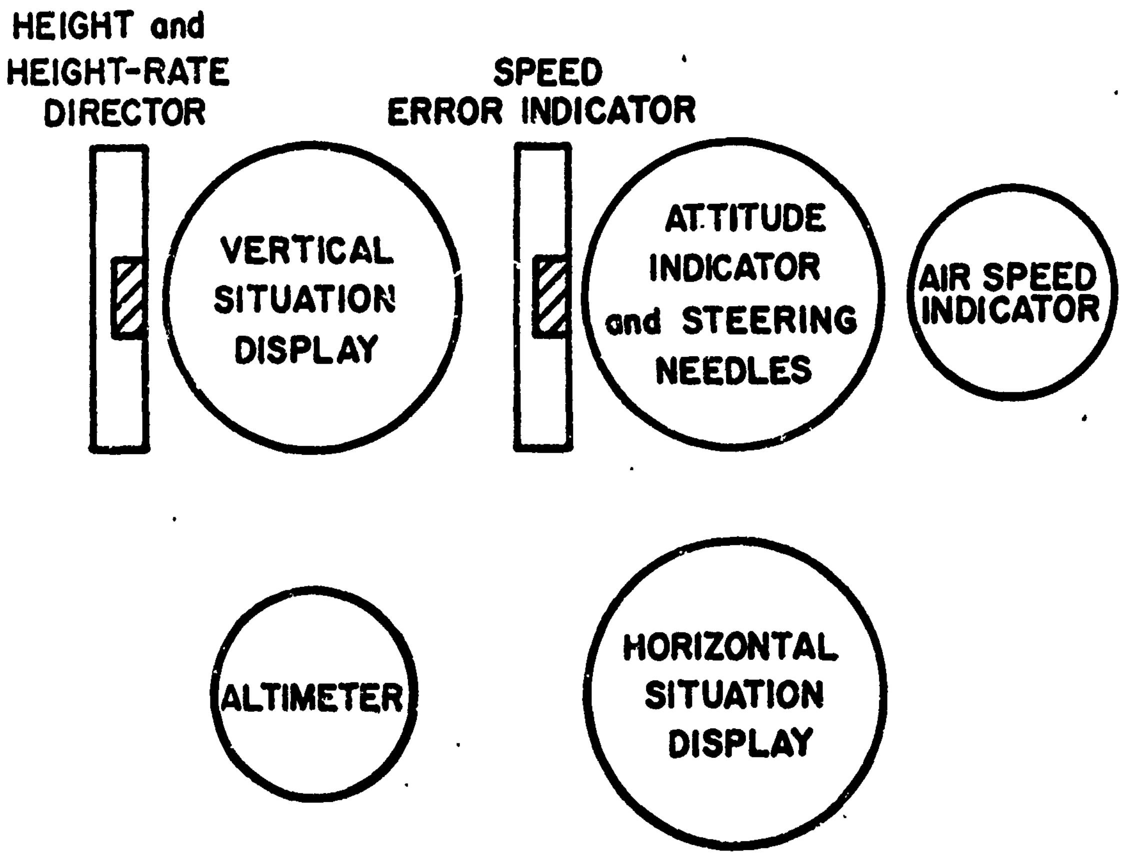


FIGURE 16. SUGGESTED FLIGHT INSTRUMENT ARRANGEMENT